Exoplanet Imaging from Space: Path to Finding Another Earth

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Are we Alone?

When you dream,
What do you dream about?
When you dream,
What do you dream about?
Do you dream about
Music or mathematics
Or planets too far for the eye?

-- Barenaked Ladies
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Finding planets around other stars, and in particular Earthlike planets, ignites the public imagination and pushes the limits of both science and engineering.
NASA discovers Earth-sized planet that may sustain life
– CNN, April 18, 2014
NASA discovers Earth-sized planet that may sustain life
– CNN, April 18, 2014
NASA discovers Earth-sized planet that may sustain life
– CNN, April 18, 2014
An Epochal Discovery: A Habitable Planet Orbits Our Neighboring Star - The Atlantic
Proxima Centauri b

The Radial Velocity Signal
Proxima Centauri b

An Epochal Discovery: A Habitable Planet Orbits Our Neighboring Star

Relative size of Mercury’s Orbit

from NYT.com
Known Exoplanets - Statistics
Known Exoplanets - Statistics

We want to image them here!

- Direct Imaged
- Microlensing
- Transit+RV
- Transit only
- RV only
Direct Imaging Today

HR8799 cde

CHARIS at Subaru Telescope
Direct Imaging Today

HR 8799 b (at 10 pc)

- $\text{H}_2\text{O}$
- $\text{CH}_4$
- $\text{CH}_4 + \text{H}_2\text{O}$
- $\text{CO}$
Why Direct Imaging?

1. Statistical Properties – probing the outer parts of solar systems
2. Detailed Characterization – determining the composition and detailed state of planetary atmospheres.
3. Formation mechanisms – measuring parameters that constrain formation theories.
4. Ultimately – determining whether life-bearing planets are common.
5. Imaging is visually compelling – It’s cool!
Why is exoplanet imaging such a technical challenge?
Star & Planet with Diffraction

\[ E_i \rightarrow A(x) \]

\[ E_i \rightarrow A(x) \]
Star & Planet with Diffraction
Star & Planet with Diffraction

\[ P_c(\omega) = |\mathcal{F}\{E_i A(x)\}|^2 \]

On-Axis Point Spread Function

\[ P_c(\omega) = |\mathcal{F}\{E_i e^{-x \theta / \lambda} A(x)\}|^2 \]

Off-Axis Point Spread Function
Proxima Centauri
From Hubble
Proxima Centauri
From Hubble
High-Contrast Imaging Laboratory, Princeton University

Proxima Centauri From Hubble

Diffraction Spikes
High-Contrast Imaging Laboratory, Princeton University

Proxima Centauri From Hubble

Diffraction Spikes

“Speckle” due to aberrations
Proxima Centauri
From Hubble

Planet is here

Diffraction Spikes

“Speckle” due to aberrations
How do we solve these problems to get an image of a nearby exoplanet?

- Go to space to avoid atmospheric turbulence and absorption
- Build a large telescope (> 2-4 m)
- Build a coronagraph or starshade to control diffraction
- Carefully control telescope and optical system to ensure stability
- Employ advanced processing techniques to extract planets from “speckle” background
Coronagraphs

A Coronagraph uses internal optics to reduce diffracted light from a region in the image plane where we search for a planet.

The classical Lyot Coronagraph

from Matt Kenworthy, University of Leiden
Pupil Apodization to Reshape PSF

Shaped pupil contrast independent of wavelength.
Pupil Apodization to Reshape PSF

Shaped pupil contrast independent of wavelength.
Pupil Apodization to Reshape PSF

It’s Simple!

Shaped pupil contrast independent of wavelength.
Shaped Pupil Zoo

<table>
<thead>
<tr>
<th>Ring</th>
<th>Barcode</th>
<th>Cross-barcode</th>
<th>Spiderweb</th>
<th>Starshape</th>
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<tbody>
<tr>
<td><img src="image1" alt="Ring Mask" /></td>
<td><img src="image2" alt="Barcode Mask" /></td>
<td><img src="image3" alt="Cross-barcode Mask" /></td>
<td><img src="image4" alt="Spiderweb Mask" /></td>
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<td><img src="image8" alt="Cross-barcode PSF" /></td>
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<tr>
<td><img src="image11" alt="Ring S-K" /></td>
<td><img src="image12" alt="Early ripple designs" /></td>
<td><img src="image13" alt="ripple1" /></td>
<td><img src="image14" alt="ripple2" /></td>
<td><img src="image15" alt="ripple3" /></td>
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- Shaped pupils: $A(x,y)$ is zero-one valued (holes in masks)
- Advantages:
  - simple to manufacture
  - inherently broadband
  - minimally sensitive to aberrations
  - no off-axis degradation of PSF
- Disadvantages:
  - throughput (though roughly the same as 8th order Lyot coronagraph)
  - IWA (better IWA can be achieved through less discovery space or greater simplicity)

Pupils designed via optimization under certain constraints
Etched Ripple 3 Mask at JPL MDL

Design

The narrowest opening may be as small as 2 µm

SEM Images

1 micron precision

Courtesy of K. Balasubramanian, JPL MDL
Etched Ripple 3 Mask at JPL MDL

The narrowest opening may be as small as 2 µm.

Figure 3. SEM image of the Ripple3 mask (detail) showing the dashes from the top. On the right is a 3D cross-section of the sidewalls on the dashes. Light enters from the top. Vertical sidewalls lead to undesired interactions with the electrical field that degrade contrast.

4. TESTBED LAYOUT

The experiments in this paper were conducted on the High Contrast Imaging Testbed (HCIT) [2,17] at the Jet Propulsion Laboratory (JPL), based on prior testing and development at the Princeton testbed [18,4]. It is a state-of-the-art facility for testing high contrast coronagraph designs and wavefront control systems. It consists of a vacuum chamber, a vibration isolated optical bench, a flexible optical configuration that accepts at least the BLC and SPC coronagraphs, a 32x32-actuator Xinetics deformable mirror, a supercontinuum source that can be filtered either with a broadband 10% bandpass filter (760nm-840nm) or one of 5 spectrally adjacent narrowband 2% filters within that 10% band, and finally a computer interface that can control everything remotely. HCIT is described in more detail in [2] and [17].

The optical layout is shown in Figure 4 and is very simple if the main functional components in the layout are highlighted. OAP1collimates the beam and the DM is placed at the first pupil plane. This pupil plane is then reimaged to a second pupil plane where the shaped pupil is located. OAP4 brings the beam to first focus, where the so-called “bowtie” mask is placed that blocks the bright parts of the PSF. This image plane is the reimaged to a second image plane where the CCD camera is placed. (The purpose of the bowtie mask is to prevent blooming and related artifacts on the CCD, but it is not necessary in principle.)

It should be noted that the shaped pupil is tilted by about 4 degrees with respect to the optical axis in order to avoid back-reflections. Such a tilt means that the incident field now sees tilted sidewalls instead of vertical ones. Assuming geometrical optics, this tilt will slightly reduce the effective area of each mask opening. This reduction will create an error in the image plane on the order of contrast, but will luckily actually cancel some of the error due to the 0.5 enlargement of the openings mentioned above that was caused by an overetch. However, geometrical optics is probably not a good approximation in this case and these effects may be dominated by the increased vector interactions with the tilted sidewall. A tapered sidewall mask will eliminate this issue.
Wavefront Aberrations
Atmospheric distortions and imperfect optics degrade contrast

\[ E_i(1 + \epsilon(x))e^{i\phi_a(x)} \]

Coronagraph

\[ A_o(x)e^{i\phi(x)} \]

Aberrations significantly degrade contrast: \(10^{10}\) ~ \(10^5\)
Wavefront Aberrations

Atmospheric distortions and imperfect optics degrade contrast

\[ E_i(1 + \epsilon(x))e^{i\phi_a(x)} \]

Coronagraph

\[ A_o(x)e^{i\phi(x)} \]

Aberrations significantly degrade contrast: \(10^{10} \sim 10^5\)
Wavefront Aberrations

Atmospheric distortions and imperfect optics degrade contrast

\[ E_i (1 + \epsilon(x,y)) \]

Aberrations significantly degrade contrast: \(~10^5\)

Proxima Centauri From Hubble

\[ x(\lambda/D) \]

\[ y(\lambda/D) \]

PSF without Correction
Focal Plane Wavefront Control as Stochastic Optimization

1. The goal of FPWC is to minimize the contrast in dark holes

$$\min x_k^T x_k$$

2. In reality, since we only have the estimate, \( \hat{x}_{k-1} = \langle x_{k-1} \rangle \), and covariance matrix, \( P_{k-1} \), of \( x_{k-1} \). FPWC problem can be formulated as stochastic optimization

$$\min \langle x_k^T x_k \rangle$$

$$\iff \min \langle x_{k-1}^T (x_{k-1}) + 2\langle x_{k-1}^T \rangle G u_k + \langle G u_k \rangle^T G u_k + Tr(Q_k) + Tr(P_{k-1})$$

$$P_{k-1} = \langle x_{k-1} x_{k-1}^T \rangle - \langle x_{k-1} \rangle \langle x_{k-1} \rangle^T, Q_k = \langle w_k w_k^T \rangle,$$

2. Wavefront Controller

$$\min \langle x_{k-1}^T (x_{k-1}) + 2\langle x_{k-1}^T \rangle G u_k + \langle G u_k \rangle^T G u_k + Tr(Q_k)$$

1. Wavefront Estimator

$$\min Tr(P_{k-1})$$

3. System Identification

$$\min Tr(Q_k)$$
Deformable Mirrors

Xinetics Electrorestrictive MEMS Deformable Mirror (BMC)

Continuous facesheet
FOV determined by number of actuators
Model surface as linear sum of basis functions
Usually influence function as basis function
  Measured response from a single poked actuator
  Approximately Gaussian shape
At least 2 DMs are required for broadband amplitude control on both sides of image.

Princeton HCIL Schematic
At least 2 DMs are required for broadband amplitude control on both sides of image.
Direct Imaging with a Coronagraph
Scheduled to enter Phase B in April
Tip/Tilt Sensing & Adaptive Control

Controller on

Tilt in mas

Iteration number

Tilt in mas

Iteration number

True value

Estimate

0.4 mas
Can we image Earth-like planets with WFIRST?

No, but . . . .
Direct Imaging with a Starshade
An Alternative Approach–Starshades

July 11, 1991

August 11, 1999
An Alternative Approach—Starshades

Block the star but let the planet pass.
High-Contrast Imaging Laboratory, Princeton University

Separation distance
30,000 – 50,000 km
±250 km

±1m lateral control

heliocentric Earth drift-away or L2 orbit

Starshade diameter 34m

Inner Working Angle

Case Study | Parameters | Observing Bands
--- | --- | ---
20m inner disk | Bandpass (nm) | Blue | Green | Red
28 7m petals | IWA (mas) | 70 | 100 | 118
Separation (Mm) | 50 | 35 | 30
Flying a starshade with WFIRST opens the possibility of imaging an Earth-like planet next decade.
Final TDEM 1 Prototype Petal

Final assembled TDEM prototype petal with FARO CMM arm used for edge installation metrology.

Edges measured to less than 5 microns and manufactured to better than 25 microns.

25 microns is about 1/4 the width of a human hair.

Mean contrast of $2.1 \times 10^{-11}$ and 95% confidence level of $4 \times 10^{-11}$
Gen 2 Deployment (no metrology)
Gen 2 Deployment (no metrology)
Primary Milestone:
- Demonstrate $10^{-9}$ suppression at flight-like Fresnel number

- Starshade diameter:
  - 34.7 mm (to peak apodization)
  - 50 mm (to outer starshade)

- Wavelength:
  - 633 (638) nm

- Aperture diameter:
  - 4 mm
  - ~4 resolution elements across SS

- Fresnel Number:
  - 27
Latest Results

Mask 2

*Work by Yunjong Kim

Mask design has 7.5 μm valley

Est. 0.5 μm over-etch

$S_{4.9} = 4.6 \times 10^{-8}$

Avg contrast: $3.5 \times 10^{-10}$

A tech demo for . . . .

HabEx

starshade

4-m aperture

coronagraph

LUVOIR

9-15 m aperture

Two NASA Science and Technology Definition Teams studying next generation observatory with focus on Exo-Earth characterization.
Breakthrough Starshot

A Navigation Problem!